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P-24: Terrain Texture and 3-D Object Cues in the Control of Heading in Simulated Flight

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Abstract.

The effects of terrain texture type and the height and density of 3D objects on heading control were studied in two experiments conducted in a high-performance flight simulator. The results suggest an orthogonal-extension principle which relates performance to the number and length of contours that are perpendicular to the ground plane, and also begin to define the stimulus conditions for which the principle is valid.

1. Introduction

Of the various visual cues that specify heading (direction of travel), one of the most important is the motion parallax associated with the optic flow produced when an observer moves through the environment [1]. Motion parallax refers to differential retinal-image motion produced by objects located at different distances from a moving observer. This pattern of relative motion is involved in directing locomotion, controlling postural balance, steering vehicles, and performing other tasks [2].

In the present study, we investigated the ability of observers to use motion parallax information in a high-performance flight simulator to control and maintain heading toward a ground target in the presence of a crosswind. Visual cues related to terrain texture and objects (trees) were studied in order to determine their role in providing motion parallax information for the control of heading.

In Experiment 1, we examined three terrain textures, each presented with and without trees: a gray or non-textured terrain, a random-noise terrain, and a simulated geospecific terrain. The untextured terrain was included in order to assess whether a lateral displacement of the target could function as a heading cue when motion parallax information was degraded. The noise terrain was included for comparison with the results of Geri, *et al.* [3], who noted, in the context of low-altitude flight, certain similarities in the spatial frequency spectra of low-pass, random-noise terrain and geospecific imagery. The simulated geospecific terrain was included in an attempt to verify its similarity to low-pass, random-noise textures in the context of heading performance. Finally, trees were included in order to examine whether objects, extending above the ground plane, would provide enriched motion-parallax cues that would improve heading performance.

In Experiment 2, we investigated one terrain texture, the gray non-textured terrain, presented with trees of varying height and density. We did so in order to determine whether motion parallax information might be spatially integrated along and across the vertical contours of the trees

Our heading task was a simplified version of the control tasks actually performed by pilots. For example, flying an airplane involves fourth-order control responses [4]. With our first-order control task, we investigated optical variables that affect performance when observers view synthetic vision displays.

2. Methods

General. Seven observers with normal vision participated in each experiment. The test databases were generated, and flight over the terrain was simulated, using a commercial PC-based image generation system (MetaVR Inc.). During the flight, the direction of travel was perturbed laterally by simulated crosswinds defined by the sum of three sinusoids of various frequencies, magnitudes, and phases. The test imagery was displayed on three channels of a wide-field, rear-projection system [5] using full-color CRT projectors (Barco, Inc.). The test imagery subtended 180° (horizontal) × 63° (vertical) at a viewing distance of 94 cm. Each display channel provided 1600 × 1200 pixels, at an update rate of 60 Hz. A joystick, interfaced to the PC, was used by the observers to control heading. During each 20 sec trial, observers flew at a constant speed of 90 m/sec and a constant altitude of 30 m.

The observers were instructed to maintain a straight and direct path toward a target (a building initially positioned 1.8 km from the starting point) as their flight direction was altered by crosswinds. Simulated crosswind gusts perturbed the observers' direction and they had to compensate by pointing the virtual vehicle into the wind and side-slip or 'crab' the vehicle in a straight line toward the target. To prevent the use of position-based cues, the magnitude and direction of the crosswind was varied over time, while a 90-degree angle to the long axis of the aircraft was maintained. The observer continuously varied the directional component of the aircraft's velocity to keep the aircraft moving in a direct path to the target relying on motion parallax information provided by the optic flow. Heading control error was defined as the deviation, in degrees, from a straight path to the target. A root mean squared (RMS) error, which served as the dependent variable, was calculated from 80 error measurements obtained at 250-msec intervals over each 20-sec trial.

Experiment 1. There were a total of six test databases each measuring 5 km × 5 km, and corresponding to each combination of three texture conditions [gray (untextured), low-pass noise, geospecific] and two tree conditions (trees, no-trees). Shown in Fig. 1 is the observers' view of the test imagery, in this case the noise/tree condition, as it appeared on the front channel.

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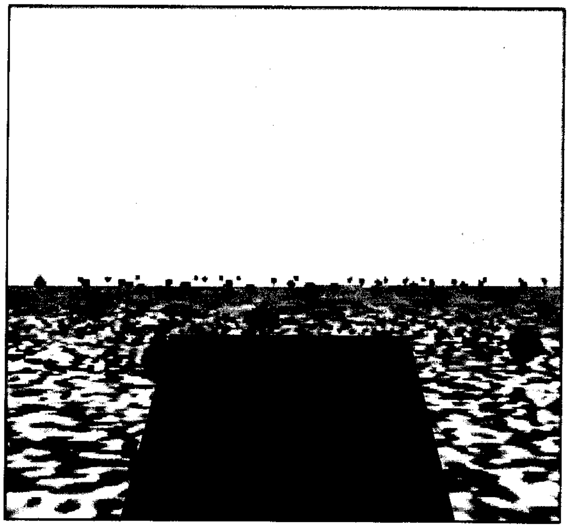

Figure 1. Observer's view of test imagery. Shown is the noise/tree condition. The dark area at the bottom of the image indicates the portion of the visual scene occluded by the aircraft cockpit.

Experiment 2. There were a total of 21 test databases, each measuring 5 km × 5 km, and each constructed using a gray (untextured) terrain. Twenty of the databases were obtained by combining each of the four tree densities with each of the five tree heights. One test database (control) consisted of only the target building, and thus corresponded to the gray/no-tree condition of Experiment 1.

3. Results

Experiment 1. Shown in Figure 2 are the changes in the RMS error in heading control associated with various combinations of terrain types and trees (3-D objects). When the data are combined across the tree and no-tree conditions, there is a significant change in RMS error across the various terrain types ($F_{2,10}$=13.3, p<0.02). When the data are combined across all terrain types, the presence of trees significantly reduced the RMS error ($F_{1,5}$=49, p<0.002). There also was a significant interaction between the tree and texture-type factors ($F_{2,10}$=10.7, p<0.03)]. With respect to this interaction, when no trees were present, the presence of either the noise or real-world textures reduced the RMS error as compared to the gray (untextured) condition ($F_{2,12}$=13.8, p<0.01); when trees were present, RMS error was low and it did not significantly change across texture types (p>0.05).

Experiment 2. Shown in Fig. 3 is the RMS error for various combinations of tree height and tree density. When the data are combined across the tree density conditions, RMS error significantly decreased as tree height was increased ($F_{5,30}$=47.4, p<0.001). When the data are combined across the different tree heights, RMS error significantly decreased as tree density was increased ($F_{4,24}$=31.8, p<0.001). There also was a significant interaction between tree height and tree density ($F_{12,72}$=2.5, p<0.01). With regard to this interaction, for each density, performance improved as tree height was increased (all p<0.05), and the largest improvement occurred for the 64 trees/km^2 condition.

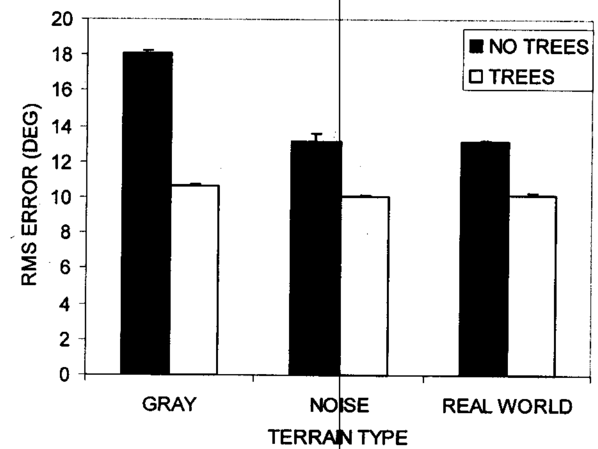

Figure 2. RMS error for six different combinations of terrain type and the presence or absence of trees. Each bar of the histogram represents an average of seven observers. Error bars indicate one standard error of the mean.

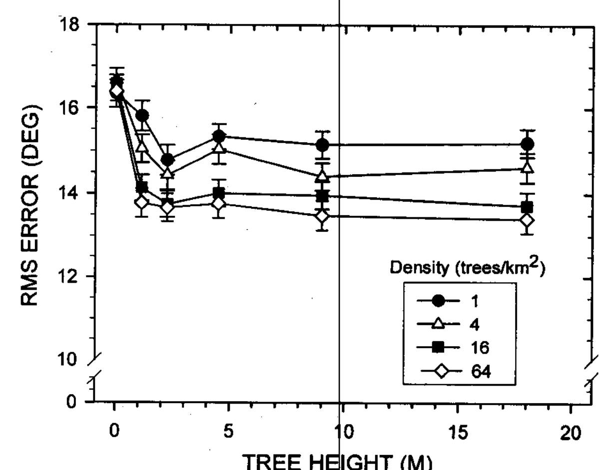

Figure 3. RMS error for various combinations of tree height and tree density. The terrain was gray and untextured. Each data point represents an average of seven observers. Error bars indicate one standard error of the mean.

4. Discussion

Significantly better heading performance was obtained with imagery consisting of either terrain texture or objects (trees) relative to the gray non-textured terrain. Interestingly, the random-noise texture produced the same level of performance as the geospecific texture. This result is consistent with the similarity in the spatial frequency spectra of random-noise textures (as used in the present study) and geospecific imagery [3], and suggests that spatial frequency content is important for the perception of optic flow [6]. Furthermore, as a practical matter, the present results suggest that noise textures may be an effective substitute for some real-world scenes in the simulation and training of tasks that involve the control of aircraft heading. However, the greatest improvement in heading control occurred when trees were present.

To understand why the presence of trees reduced RMS error, first consider that the heading task involved horizontal motion-parallax information, because the crosswinds displaced the observers laterally [2]. The primary carrier of horizontal parallax information was most likely the vertical tree boundaries. The improvement in heading control for databases consisting of more and higher trees may be related to presence of edge parallax information associated with shear in the velocity field [2]. Longuet-Higgins and Prazdny [7] (see also [8]) proposed a motion-parallax model of optic flow and heading extraction, which relies upon the existence of edge parallax information, and therefore upon real or simulated depth variation in the environment. In the present study, the presence of the trees in the foreground of a scene dynamically occluded portions of the texture elements and trees in the background, thus providing edge parallax information.

With trees of greater length and density, the parallax information may have been enhanced due to spatial integration along and across the contours of the trees, which extended vertically above the ground plane. Because the differential retinal-image motion (i.e., motion parallax) was primarily horizontal, we postulate that the best carrier of horizontal motion parallax would be the vertical tree contours along and across which the motion information could be spatially integrated.

This analysis leads us to suggest an *orthogonal-extension principle* in the use of optic flow and motion parallax information for steering a moving vehicle like an aircraft. This principle states that contours extending along an axis orthogonal to the axis in which control is to be exerted will facilitate performance. In particular, the results of Experiment 2 indicate that both the length (object height) and number (object density) of vertical contours effect heading control, Other forms of vertical extension, such as terrain elevation, may also serve as effective carriers of horizontal motion parallax information and may therefore facilitate heading performance. An untested corollary of the orthogonal-extension principle is that horizontal extensions, such as might be found in overpasses and bridges, for example, should serve as effective carriers of vertical motion-parallax information, and therefore should facilitate performance on altitude-control tasks.

Finally, the present results may also have implications for the design of synthetic-vision displays used in aviation. For example, for databases used to simulate low-altitude flight, or for airborne synthetic-vision systems used for search and rescue operations [9, 10]), the appropriate addition of extended objects to the scene may aid heading control and navigational accuracy.

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